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CATALYSING THE GLOBAL OPPORTUNITY FOR ELECTROTHERMAL ENERGY STORAGE

Technical Appendix – February 2024

FEBRUARY 2024

SUPPORTED BY Breakthrough Energy

DISCLAIMER

The numbers presented in this document, and associated reports are for generalised ETES cases, and may vary significantly from site specific numbers.

As ETES is an emerging technology segment, a significant portion of the data used for our report analysis was from expert interview sources. Whilst we endeavour to ensure that our analysis and assumptions are correct, through checks including independent reviews, some judgement is required due to the nature of this sector.

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MARKET SIZING METHODOLOGY AND APPROACH – INDUSTRY ASSUMPTIONS

First-Wave ETES Market | Rest of Addressable Market

	F&B, PULP & PAPER, AND TEXTILES	CHEMICALS	ALUMINA	CEMENT	IRON & STEEL	OTHERS
"First Wave"[2] *(process listed might be non-exhaustive)*	Majority of processes are in scope (<400°C), split using these assumptions: ▪ ETES to address 50% of 100-200°C & majority of 200-400°C ▪ Biomass in Pulp & Paper is not addressed	▪ Polymerisation (130-200°C) ▪ Bleaching (40-150°C) ▪ Boiling (90-340°C) ▪ Concentration (120-140°C)	▪ Bauxite digestion (100-300°C)	▪ Drying (20-250°C)	▪ Downstream hot rolling (350-500°C) ▪ EAF pre-heating (up to 450°C)	
Non "Drop-in"[3,] retrofit required		▪ Biorefining (up to 600°C)	▪ Calcination (800-1150°C) & pre-heating (up to 1050°C)	▪ Clinker pre-heating (up to 900°C)	▪ DRI pre-heating (300-700°C)	
Energy Transition-related Processes[4]		▪ Biorefining (up to 600°C)			▪ DRI pre-heating (300-700°C)	▪ Sustainable Aviation Fuel - Fischer Tropsch process (~250°C) ▪ Direct Air Carbon Capture (~300°C) ▪ Mining (up to 400°C)
Not included		▪ SMR[6] (400- 600°C) ▪ Steam cracking[7] (800-900°C)		▪ Alternative/ Substitute Cementous Materials[8] (SCM) production	▪ BF pre-heating (400-1250°C) ▪ BOF pre-heating (400-1700°C)	
Non-industrial[5] heat	Includes projected 2030 demand for coal repowering in 8 focus regions and a subset of district heating					

[1] **Oil and Gas is omitted** due to high usage of waste gas as heating fuel in several processes, and the temperature requirement for coking process; [2] **First-wave** is focused on steam-based processes (100-400°C) in Steel, Alumina, Cement, Chemicals, Textiles, Pulp & Paper, and Food& Beverage industries, where no adjustments are required in terms of retrofit to industrial process using the steam, i.e., the solution is "drop-in"; [3] **Not "drop-in"** use-cases where some retrofit or further engineering is required for ETES solutions to be applied, [4] **Use-cases that scale with energy transition** includes lower-carbon processes that are becoming more prominent with energy transition,, using 2050 projected numbers; [5] **Non-industrial heat** assumes ETES will address [a] 70% of district heating in 2030, [b] repowering 30% of coal plants running at 60% capacity factor (CF) in EU, North America and Oceania; [6] **Steam Methane Reforming** to produce hydrogen is better suited to be addressed by green hydrogen production through electrolysis; [7] **Steam cracking's** furnace layout is better suited to be addressed through direct electrification; [8] **Substitute Cementous Materials (SCM),** which currently covers limestone, fly ash, and calcined clay, is not calculated due to the complexity and uncertain mix if SCM in the of future cement industry; Sources: UNFCCC, International Aluminum Institute, World Steel Association, Eurostat, EuraTEX, USGS, Petrochemical Europe, Global Energy Monitor, US DoE, AREA, EPA, Encyclopedia of Materials, Arpaguas (2018), Energy Innovation.

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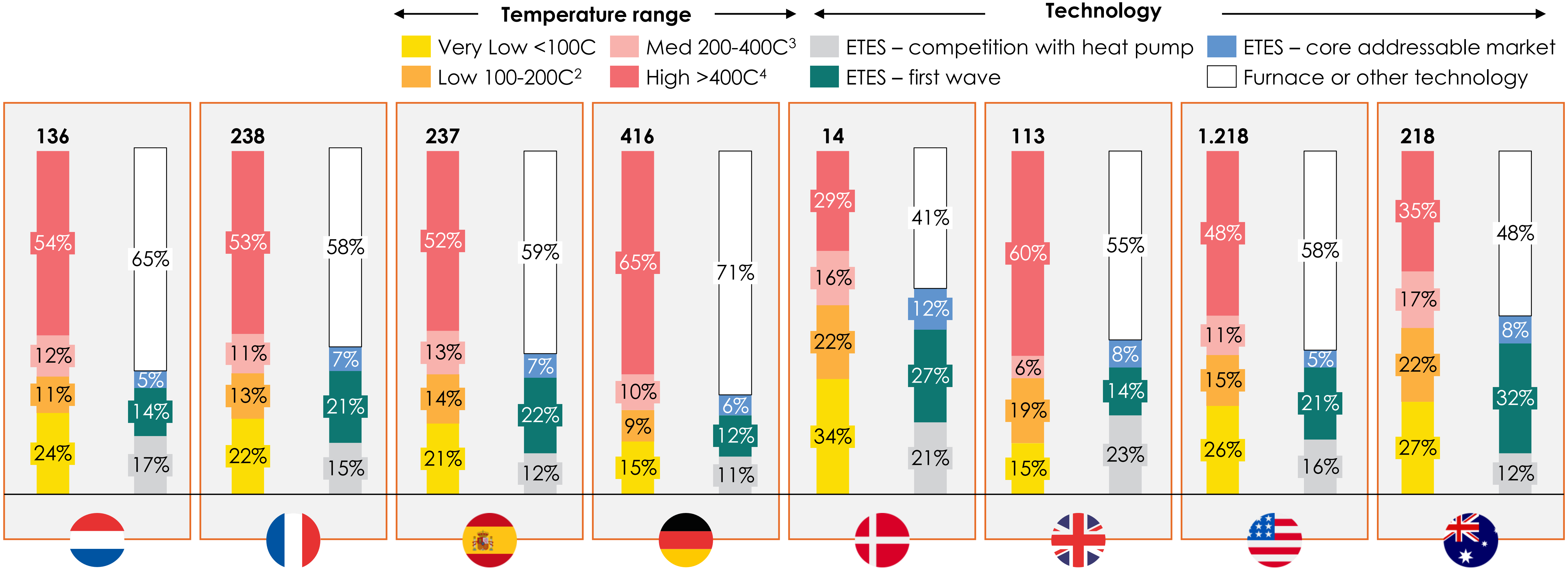
TEMPERATURE & TECHNOLOGY-BASED MARKET SIZING – FOCUS INDUSTRIES ONLY

Combustion energy usage for selected countries and industries, per country

TWh per year (2030)



[2]Includes processes such as drying, heating, sterilizing, bleaching, washing, polymerization, and steam generation. Mostly in Food & Beverage, Pulp & Paper, Textile, Chemicals, as well as Alumina digestion; [3] Mostly consist of chemical-related processes such as polymerization, hot-rolling in Steel sector, and baking or roasting in Food & Beverages; [4] High-heat processes consists of hot-rolling in Steel, as well as Green Liquor treating in Pulp and Paper; calcination in Cement & Alumina. Note: Combustion energy only considers fuel combustion, not process emissions, whereas total industry combustion energy usage include fuel combustion and processes emissions. Power sector and transport energy consumption are not considered.
Source: UNFCCC data set (2021) - except for Australia (2019), International Aluminum Institute, World Steel Association, Eurostat, EuraTEX, USGS, Petrochemical Europe

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INDIRECT POWER SYSTEM IMPACT - ASSUMPTIONS

ASSUMPTION	VALUE	UNIT	SOURCE
Additional RES capacity	0.4	MW additional renewables per MW electrical ETES	*Understanding the Role and Design Space of Demand Sinks in Low-carbon Power Systems*, Jenkins and van der Jagt, 2021. Note: the paper estimates a range of -0.1 – 0.9 MW additional renewables, of which this analysis uses the average
RES capacity factor	25	%	Systemiq analysis
CCGT Efficiency	60	%	*Compendium of energy and GHG efficient technologies and practices*, IPIECA, 2023
ETES Capacity Factor	95%		Systemiq analysis
ETES Efficiency	95%		Systemiq analysis

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IMPACT ON PEAK POWER SYSTEM LOAD

ETES Impact on Peak Load	NL	FR	ES	GER	DK	UK	US[1]	Global
Peak Load (MW)[2]	11,000	84,700	35,000	117,400	5,100	48,600	85,700	4,187,000
ETES Peak Load (MW)	3,500	6,750	7,500	9,000	650	3,000	38,000	730,000

Calculated from First Wave + Retrofit demand in TWh divided by 8320 operational hours annually (95% efficiency from 8760 hours per year)

Notes: 1) US annual generation and peak load is ERCOT only; 2) NL peak derived from 2023 annual period, from Tennet's (Dutch TSO) peak load of 23,000 MW in 2023 and interpolated using assumption NL is 40% (10,000 out of 25,000 km) of Tennet's operations; FR peak derived from 2023 annual period; ES peak derived daily peak in January 2024; GER peak derived from annual demand in 2018; UK peak derived from seasonal peak in Winter 2021; US peak derived from seasonal peak, using Summer 2023
Source: Respective countries' grid operator or Department of Energy. CBS for NL, RTE for FR, REE for ES, BDEW for GER, EnergiNet for DK, UKGOV for UK, ERCOT for US.

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CONTENTS

OVERVIEW OF LONG-DURATION ENERGY STORAGE TECHNOLOGIES AND COSTS

Low High

TECHNICAL ASSUMPTIONS

COST ASSUMPTIONS*

Long-Duration Energy Storage Technology	Efficiency (RTE%)	Capital cost			Operating cost (USD/kW-year)		
		2030	2040	Unit**	2023	2030	2040
Thermal	90%–96%	50–100	30–48	USD/kWh_t	13	13	11
Mechanical	50%–80%	50–61	50–61	USD/kWh_e	16	16	16
Electrochemical	60%–85%	206–252	165–201	USD/kWh_e	22	20	18
Chemical	30%–50%	57–69	38–46	USD/kWh_e	20	17	13

* Cost assumptions shown here correspond to a 24-hour duration
** "Capital cost – Unit" for corresponding technology indicates whether fixed operating expenditures are in USD/kWe or USD/kWt

Source: Driving to Net Zero Industry through Long Duration Energy Storage, LDES Council, 2023

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CONTENTS

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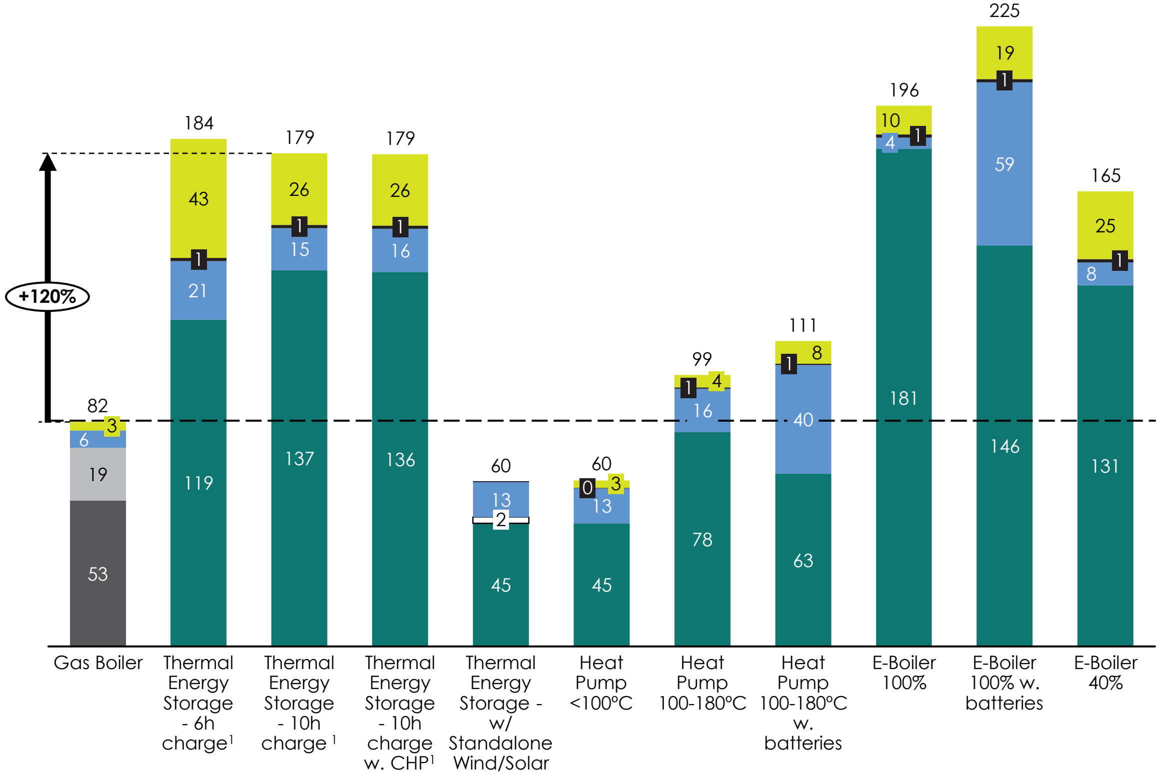
AFFORDABILITY OUTPUT | NETHERLANDS

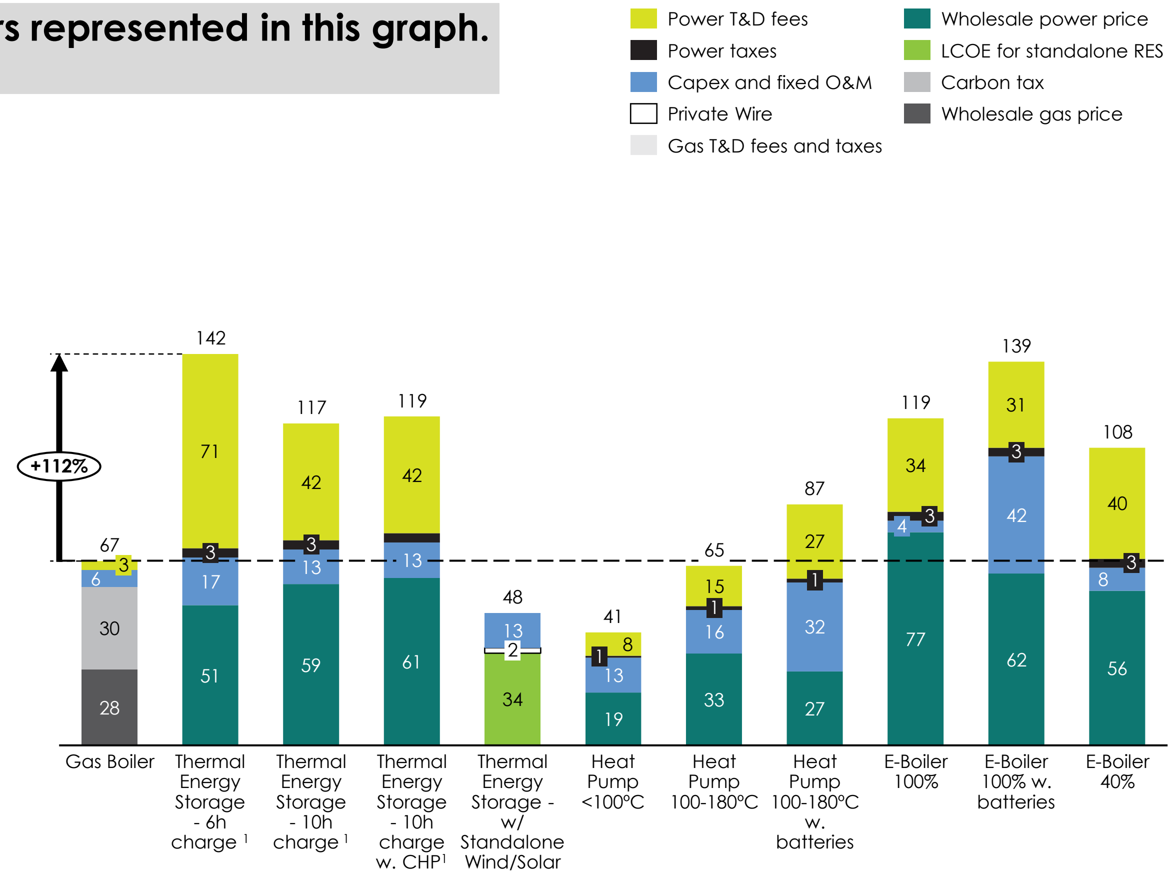
GENERALISED LEVELISED COST OF HEAT IN 2023 AND 2030 OF DIFFERENT TECHNOLOGIES

EUR/MWh thermal

LCOH for a specific case can be different from the generic numbers represented in this graph. See Main report for details of specific use case



2023 (generic set up before optimisation)



2030 (generic set up before optimisation- please see figure 10 in main report for LCOH in optimised set up)

1 Commercially available Solid State Thermal Energy Storage, Wholesale power price is for cheapest hours indicated,
Note: Does not include current subsidies schemes, changes in T&D fees and Taxes, Balancing costs. Battery storage of 10h included in battery cases, which is shorter duration than ETES thermal storage.

Sources: Tennet – Dutch network operator, P2H Cost Calculator (2022) - Agora, IRENA Remap 2030, TNO Technology Fact sheet (2015), Thermal Energy Storage (2023) - RTC, Industrial Thermal Batteries (2023) - LDES, Prospects for LDES in Germany (2022) – Aurora, NREL (2021) Commercial scale Li-Battery storage costs

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AFFORDABILITY OUTPUT | GERMANY

GENERALISED LEVELISED COST OF HEAT IN 2023 AND 2030 OF DIFFERENT TECHNOLOGIES

EUR/MWh thermal

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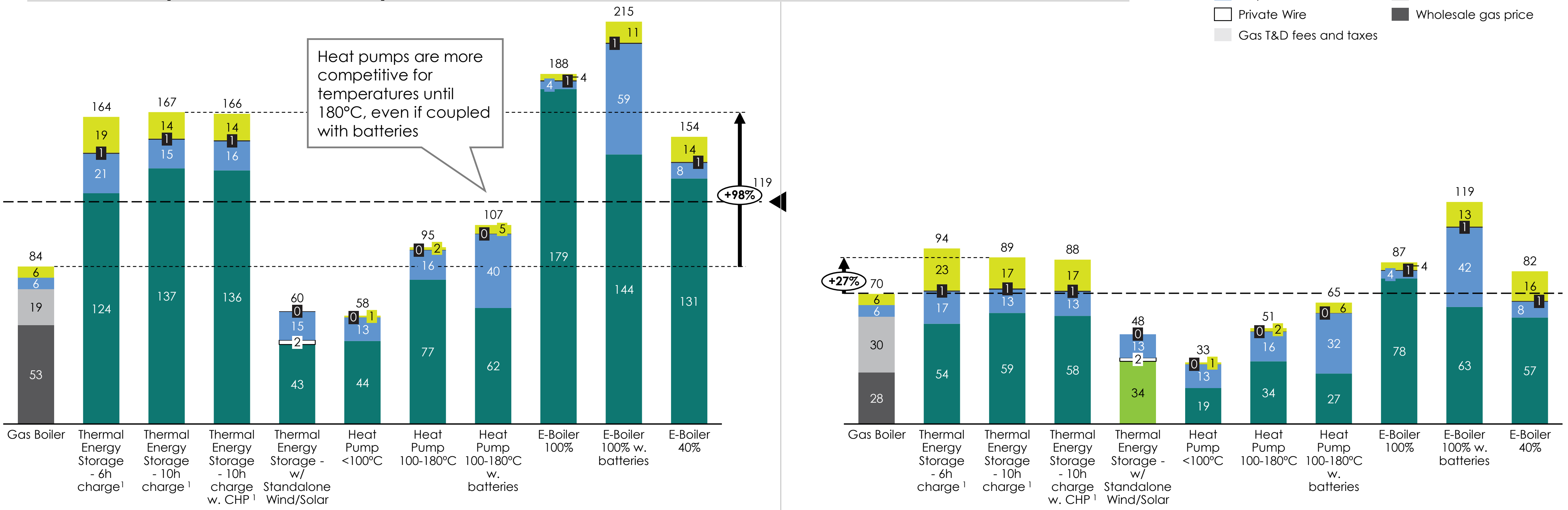

2023 (generic set up before optimisation)

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AFFORDABILITY OUTPUT | SPAIN

GENERALISED LEVELISED COST OF HEAT IN 2023 AND 2030 OF DIFFERENT TECHNOLOGIES

EUR/MWh thermal

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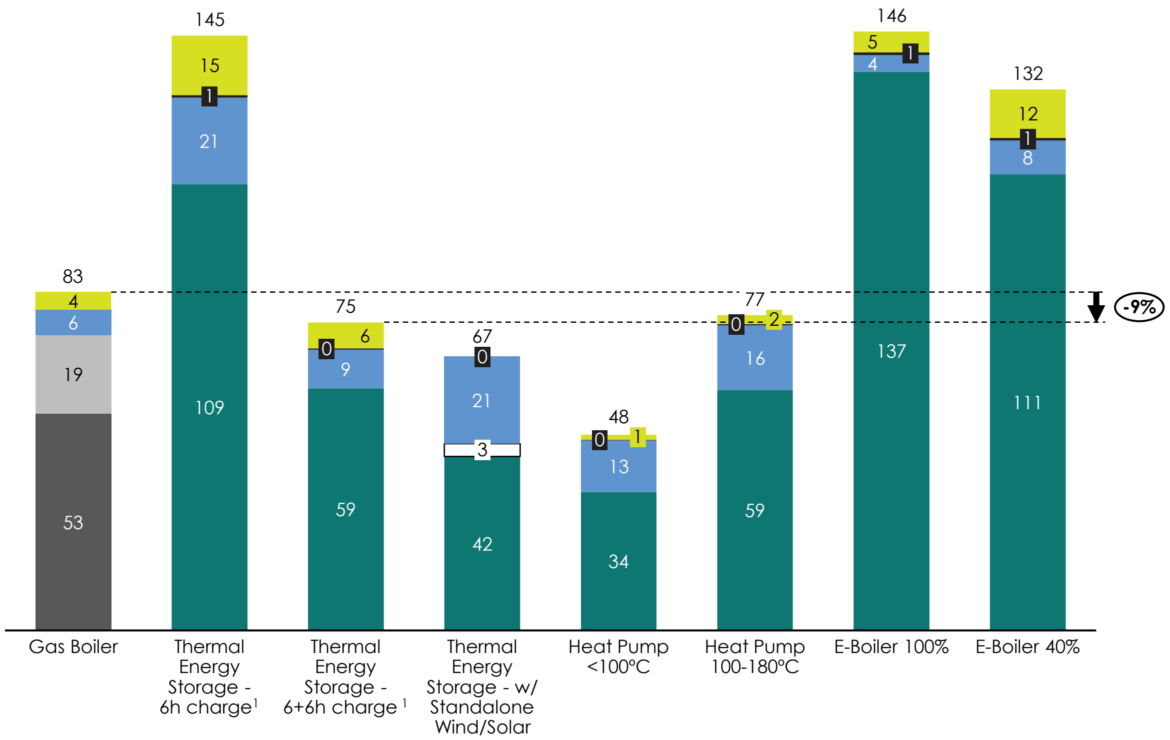
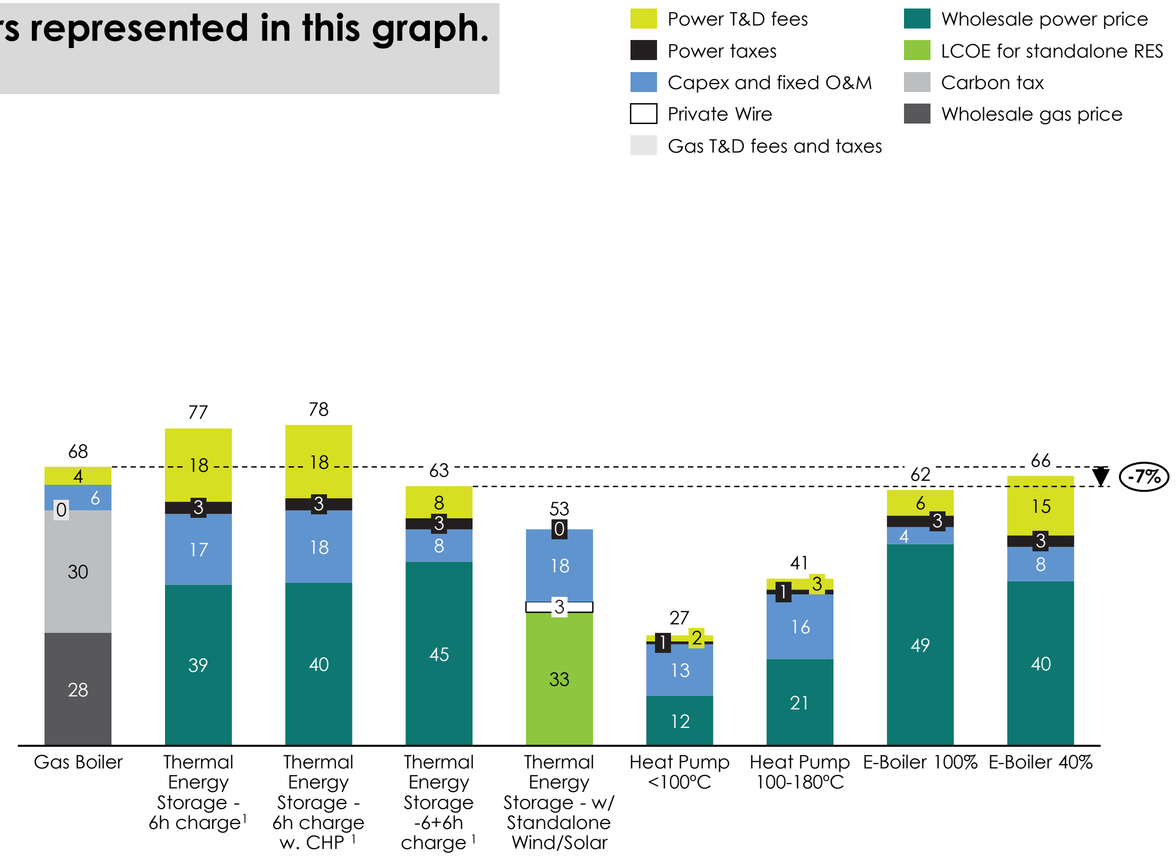


2023 (generic set up before optimisation)



2030 (generic set up before optimisation- please see figure 10 in main report for LCOH in optimised set up)

1 Commercially available Solid State Thermal Energy Storage, Wholesale power price is for cheapest hours indicated,
Note: Does not include current subsidies schemes, changes in T&D fees and Taxes, Balancing costs.

Sources: Boletin Oficial del Estado - dec. 2023, P2H Cost Calculator (2022) - Agora, IRENA Remap 2030, TNO Technology Fact sheet (2015), Thermal Energy Storage (2023) - RTC, Industrial Thermal Batteries (2023) - LDES, Prospects for LDES in Germany (2022) - Aurora

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AFFORDABILITY OUTPUT | FRANCE

GENERALISED LEVELISED COST OF HEAT IN 2023 AND 2030 OF DIFFERENT TECHNOLOGIES

EUR/MWh thermal

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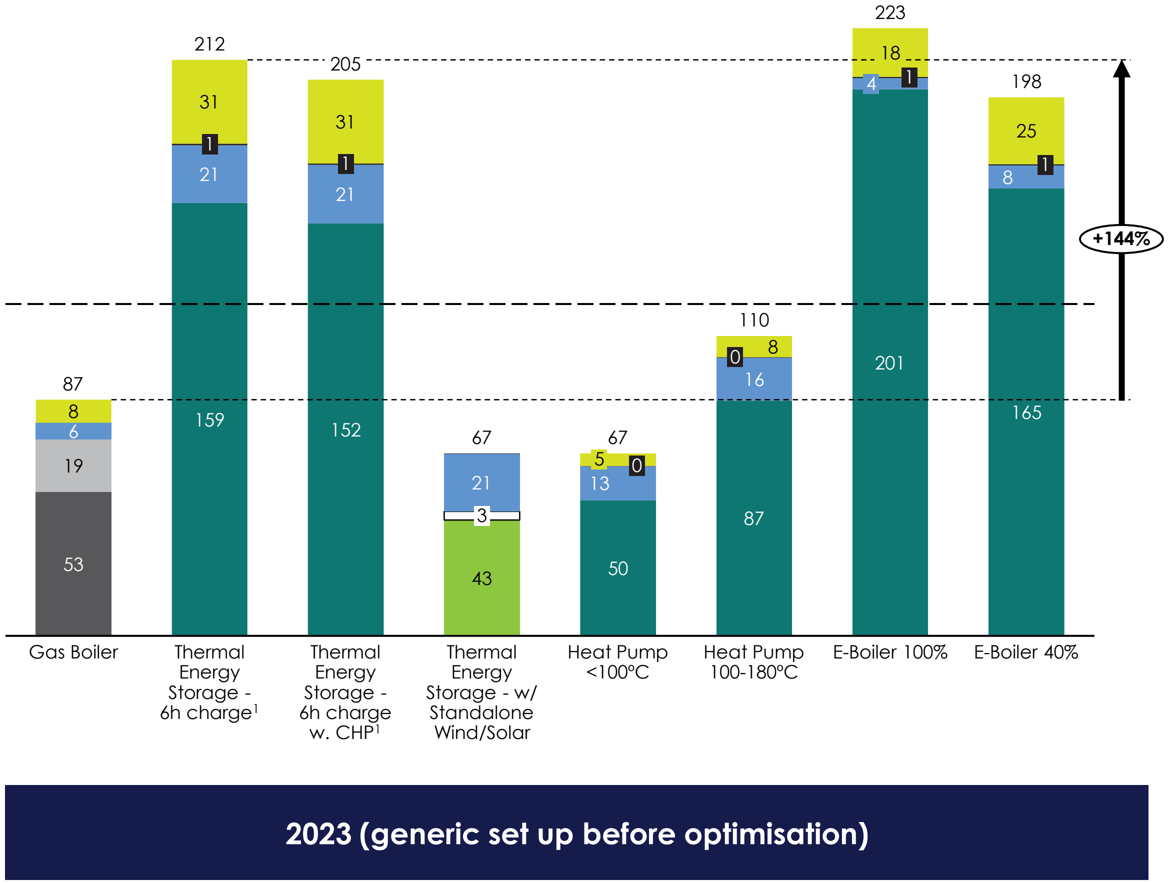

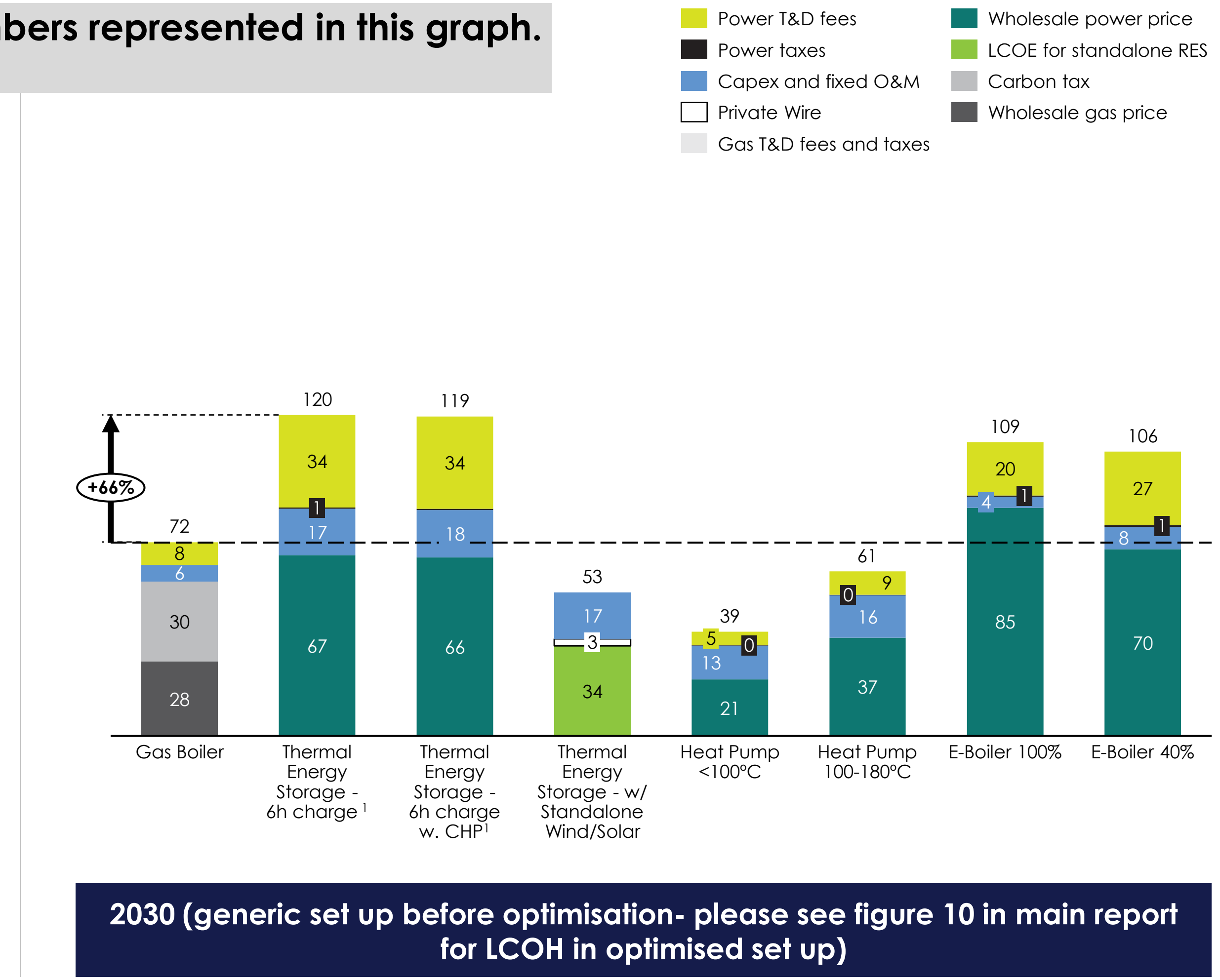

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Note: Does not include current subsidies schemes, changes in T&D fees and Taxes, Balancing costs.

Sources: Commission de Regulation de l'Energie, P2H Cost Calculator (2022) - Agora, IRENA Remap 2030, TNO Technology Fact sheet (2015), Thermal Energy Storage (2023) - RTC, Industrial Thermal Batteries (2023) - LDES, Prospects for LDES in Germany (2022) - Aurora

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AFFORDABILITY OUTPUT | DENMARK

GENERALISED LEVELISED COST OF HEAT IN 2023 AND 2030 OF DIFFERENT TECHNOLOGIES

EUR/MWh thermal

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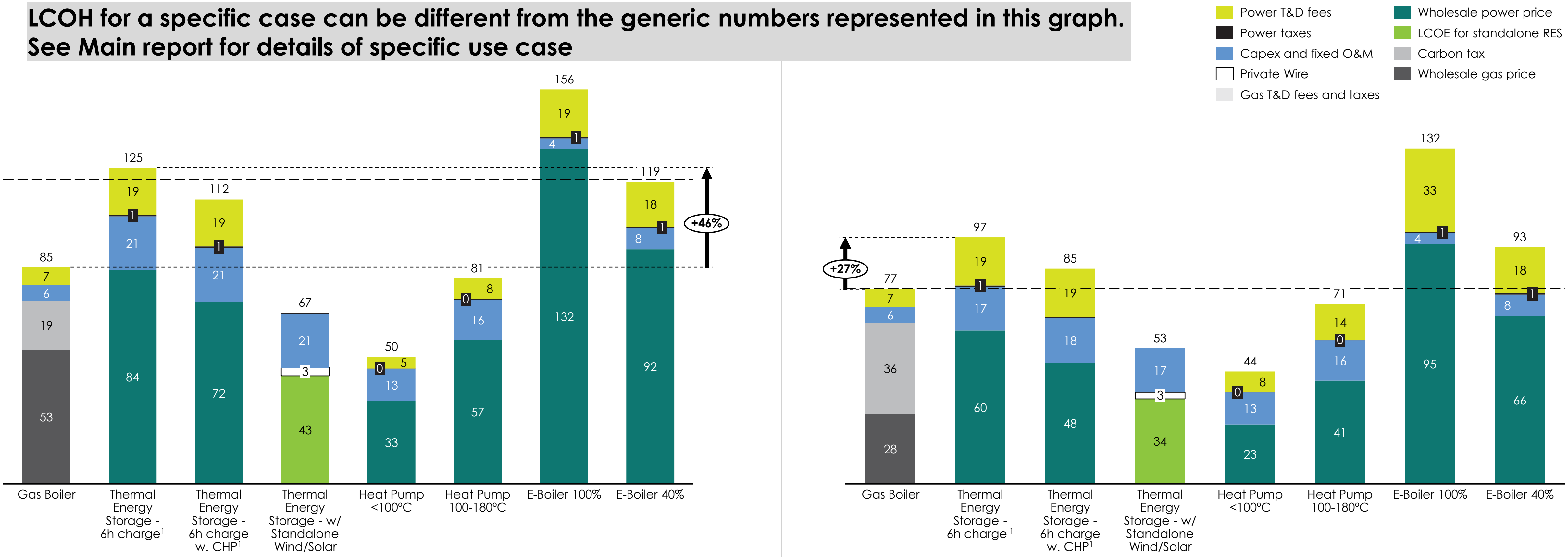

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AFFORDABILITY OUTPUT | UNITED KINGDOM

GENERALISED LEVELISED COST OF HEAT IN 2023 AND 2030 OF DIFFERENT TECHNOLOGIES

EUR/MWh thermal

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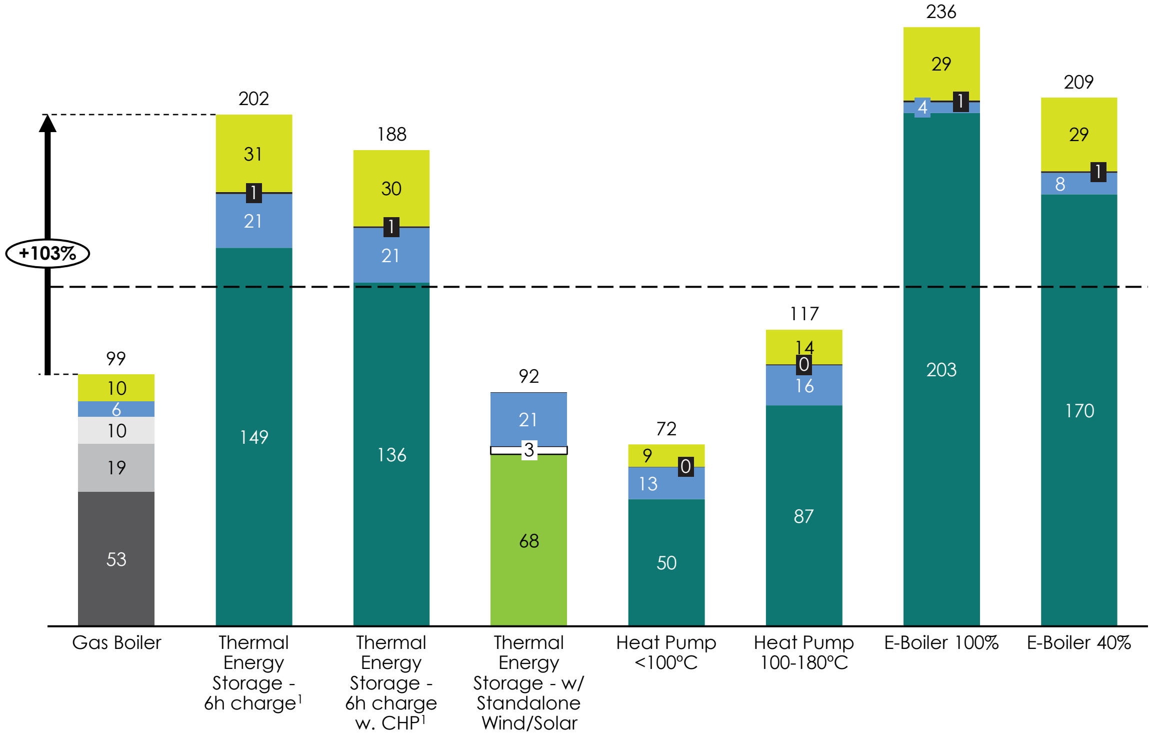
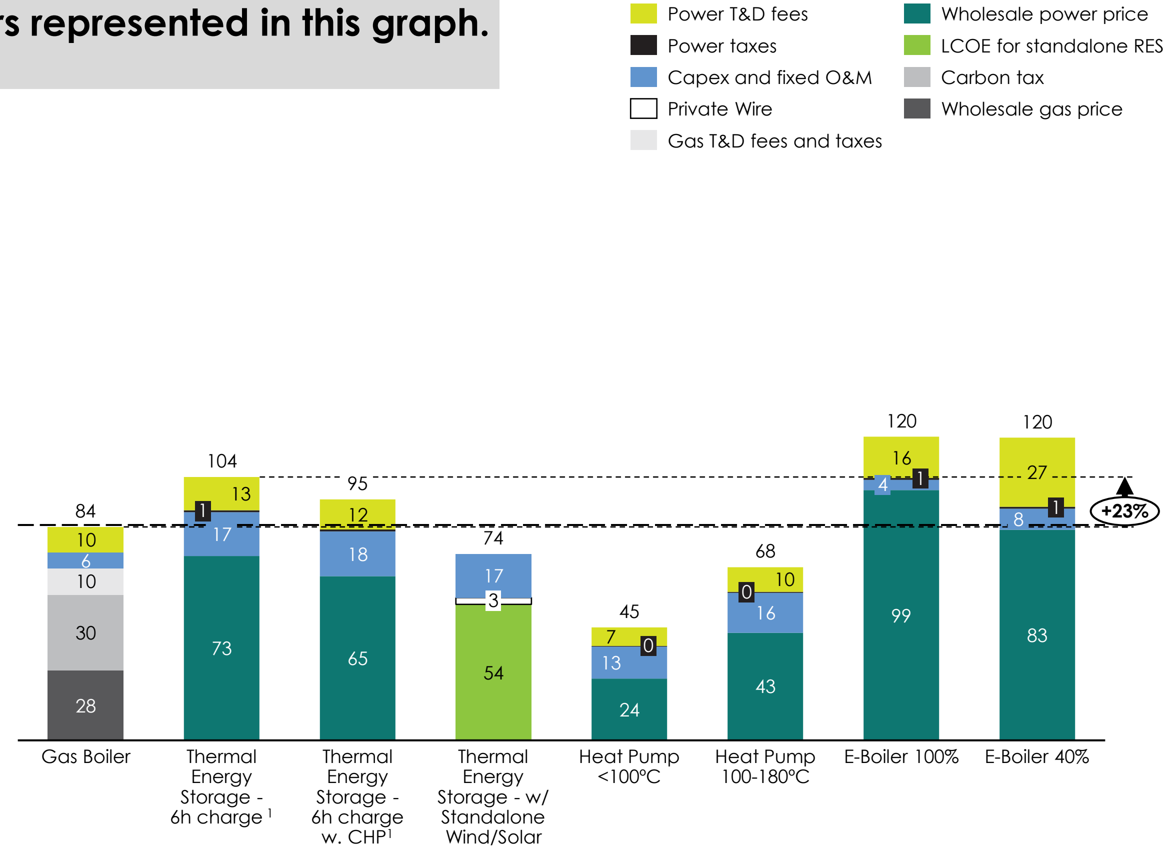


2023 (generic set up before optimisation)



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AFFORDABILITY OUTPUT | US – TEXAS ERCOT REGION

GENERALISED LEVELISED COST OF HEAT IN 2023 AND 2030 OF DIFFERENT TECHNOLOGIES

EUR/MWh thermal

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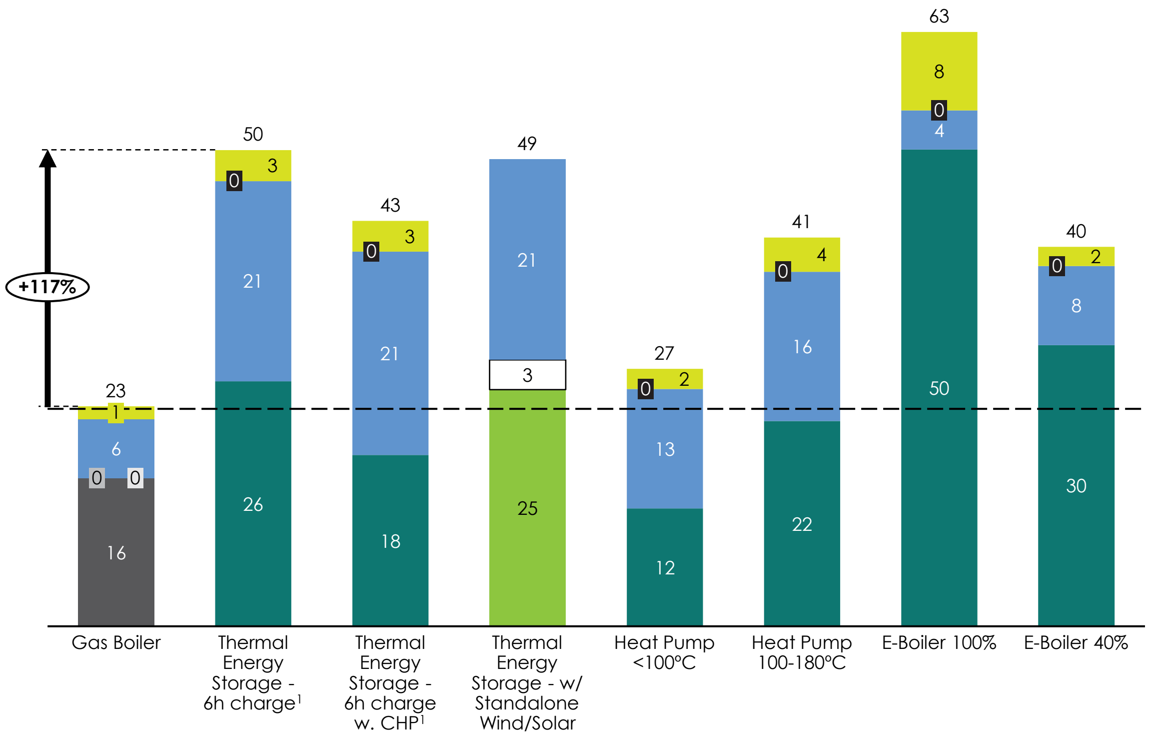
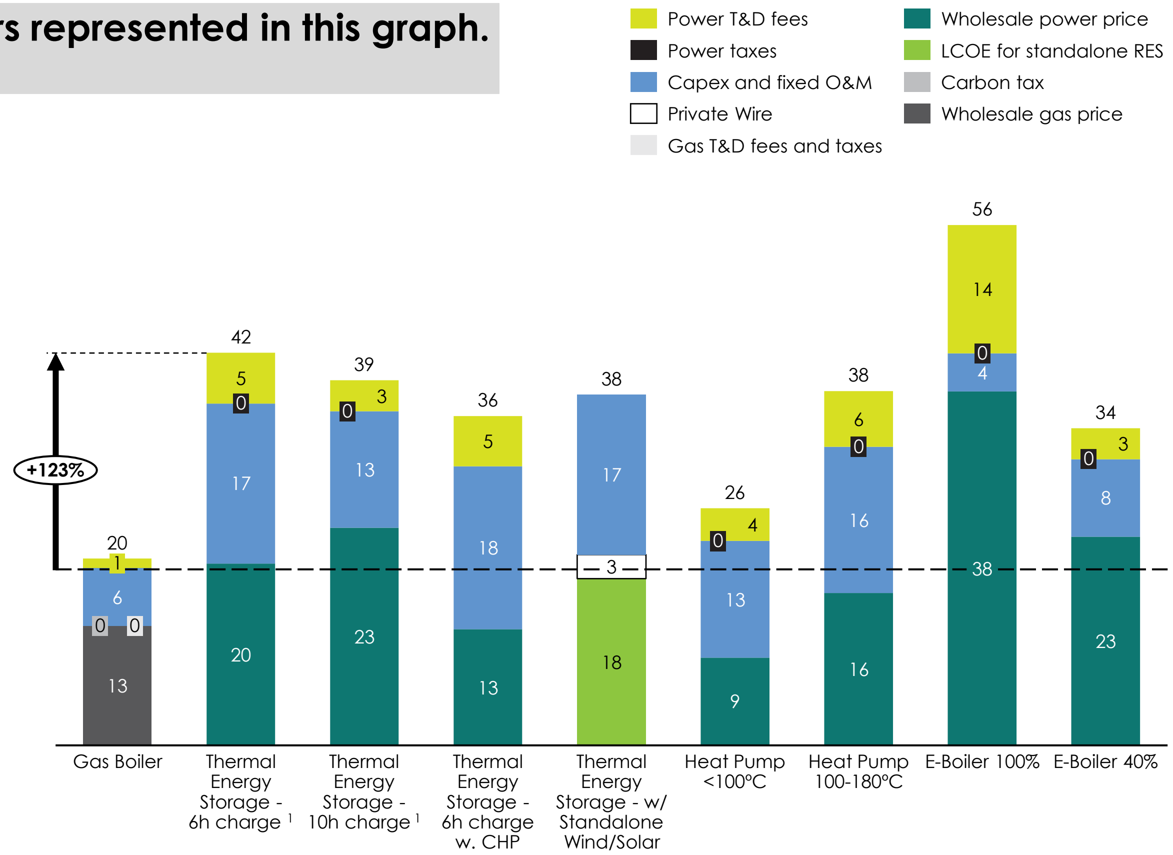


2023 (generic set up before optimisation)



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CONTENTS

AFFORDABILITY INPUTS | TECHNOLOGY ASSUMPTIONS

Lower boundary / Upper boundary

-20% capex for 2030 in ETES

Number used for each charging profile

TECHNOLOGIES	SOLUTIONS		EFFICIENCY %	2023 CAPEX EUR/kW, thermal	O&M EXPENSES EUR/MWh, thermal
ETES	6 hrs charging	Sensible Heat (solids)	92 / 97	650 / 1.650	1,8
ETES	10 hrs charging	Sensible Heat (solids)	92 / 97	650 / 1.650	1,8
ETES	12 hrs (6+6) charging	Sensible Heat (solids)	92 / 97	650 / 1.650	1,8
Heat pumps (HP)	Heat pumps < 100°C		375 / 450	1.043 / 1.500	0,4
Heat pumps (HP)	Heat pumps 100°C-180°C		230 / 260	1.035 / 2.100	0,5
E-boilers	E-boilers at 40%		98	150 / 375	1,1
E-boilers	E-boilers at 100%		98	150 / 375	1,1
Gas boilers – *Baseline case*	Brownfield		85 / 95	0	1,8 / 3,5
Gas boilers – *Baseline case*	Greenfield		85 / 95	136 / 234	1,8 / 3,5
Coal boilers – *Alternative baseline*	Brownfield		83 / 90	0	3,5 / 6,7
Coal boilers – *Alternative baseline*	Greenfield		83 / 90	136 / 268	3,5 / 6,7
ETES Alternative configurations	ETES + HP				
ETES Alternative configurations	ETES in CHP model				

ETES in CHP configuration have turbines + transformers at ~10% of ETES capex

Assumed for all technologies:

- **10 MW** capacity for thermal discharge
- **95%** capacity factor (except for e-boilers at 40%)
- **25 years lifetime** for the calculation of annualized capex
- **8.5%** cost of capital

Source: P2H Cost Calculator (2022) - Agora, IRENA Remap 2030, TNO Technology Fact sheet (2015), Thermal Energy Storage (2023) - RTC, Industrial Thermal Batteries (2023) - LDES, Prospects for LDES in Germany (2022) - Aurora

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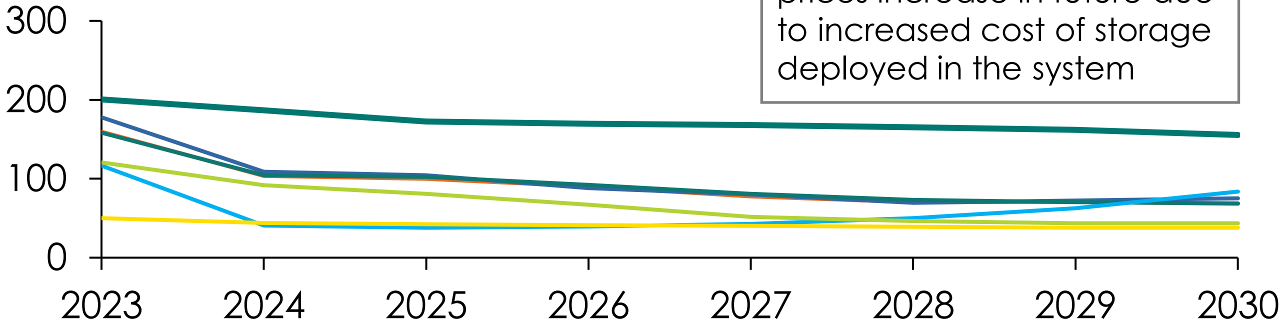
AFFORDABILITY INPUTS | WHOLESALE ELECTRICITY AND GAS ASSUMPTIONS

NL FR DE DK ES ERCOT UK

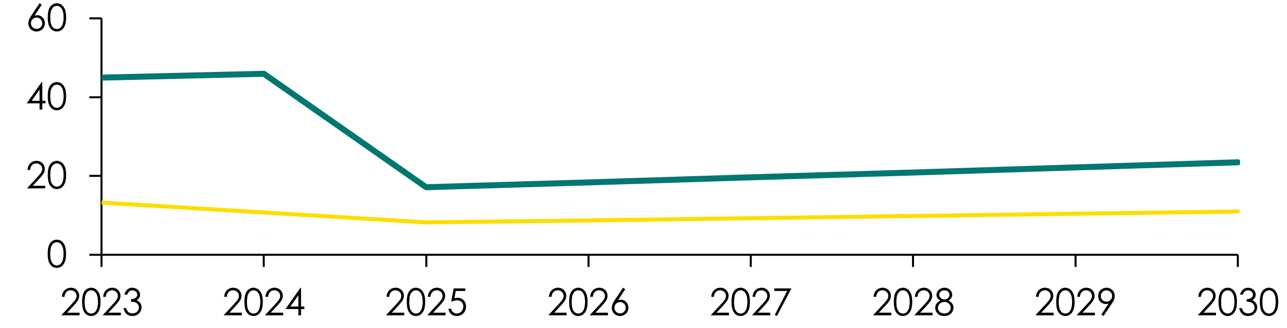
Danish baseload power prices increase in future due to increased cost of storage deployed in the system

PROJECTED BASELOAD POWER PRICE
EUR/MWh

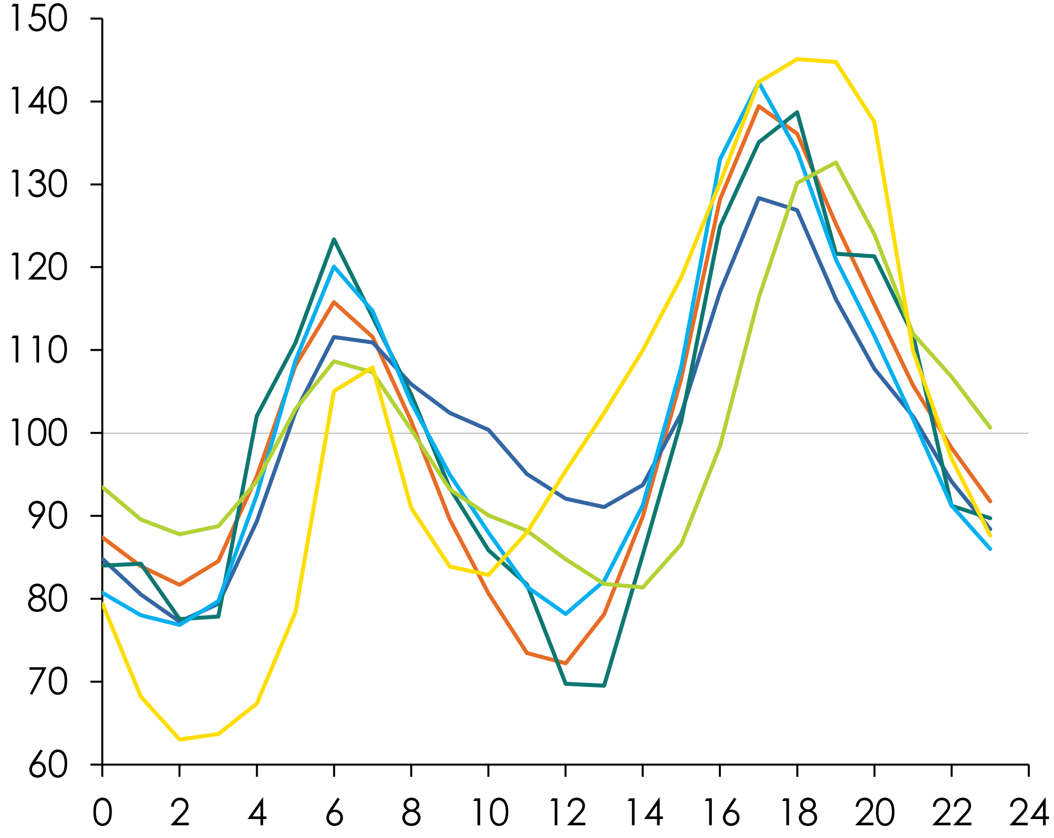


PROJECTED GAS PRICE
EUR/MWh

US average as proxy for ERCOT



POWER PRICE INTRADAY PRICE DIFFERENTIAL
% of baseload price



Source: 2022 Entso-E Power Prices, EEX Future Prices, MPP Power and Feedstock Projections (2020), Climate Change Committee - Deep-Decarbonization Pathways for UK Industry, Nord Pool, Cornwall Insight GB Power Market Outlook to 2030 Q2 2023

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AFFORDABILITY INPUTS | 2022 CHEAPEST CHARGING HOURS AS % OF DAILY AVERAGE

COUNTRY	SCENARIO	UNIT	6 hours	10 hours	14 hours
NL	BAU	% of baseload power price	**63%**	**73%**	**81%**
FR	BAU	% of baseload power price	**76%**	**82%**	**87%**
DE	BAU	% of baseload power price	**66%**	**73%**	**81%**
DK	BAU	% of baseload power price	**61%**	**70%**	**78%**
ES	BAU	% of baseload power price	**77%**	**82%**	**86%**
ERCOT	BAU	% of baseload power price	**49%**	**59%**	**66%**
UK	BAU	% of baseload power price	**71%**	**84%**	**87%**

Analysis based on **hourly prices**. B6 discount can be higher where intervals of charging shorter than an hour (e.g., 30-minutes) and associated power prices can be realised.

Input for **e-boiler – 40% case**

Input for **Heat Pump w/ battery and E-boiler w/ battery cases**

Source: Entso-E, ERCOT, Nord Pool

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AFFORDABILITY INPUTS | LCOE & LCOS ASSUMPTIONS

LCOE

COUNTRY	SCENARIO	UNIT	2023	2030
EU	Standalone Solar	EUR / MWh	40.35	30.08
EU	Standalone Wind	EUR / MWh	40.43	31.83
UK	Standalone Solar	EUR / MWh	64.44	51.00
UK	Standalone Wind	EUR / MWh	64.44	51.00
US	Standalone Solar	EUR / MWh	24.20	16.95
US	Standalone Wind	EUR / MWh	24.97	22.77

LCOS

COUNTRY	SCENARIO	UNIT	2023	2030
All	Average	EUR / MWh	54.54	37.93
All	Min	EUR / MWh	45.29	27.09
All	Max	EUR / MWh	65.99	54.88

Input for **HP + Batteries case,** assumes a 10 hours storage commercial scale Li-battery

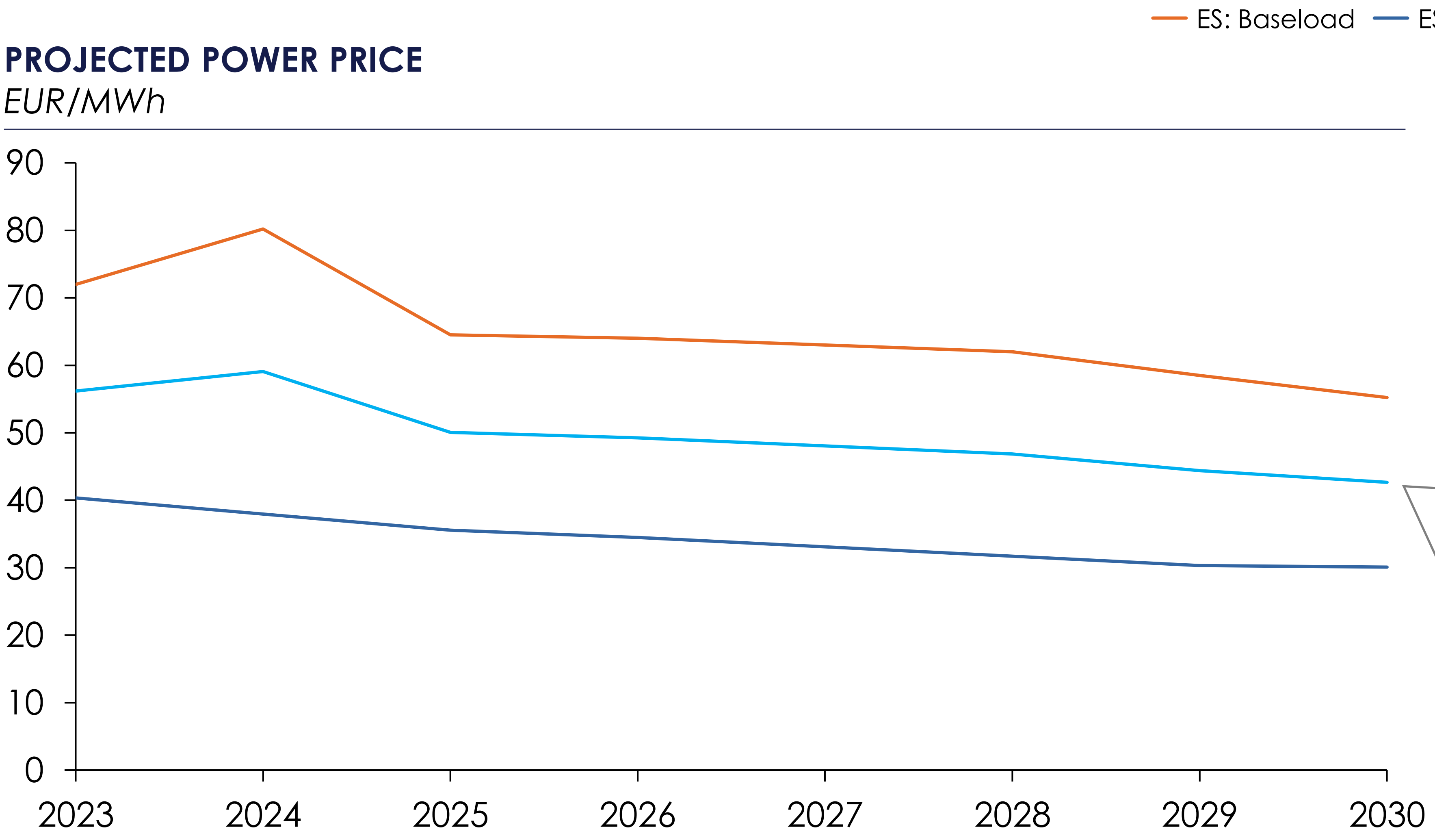
Note: Standalone Wind based on onshore wind LCOE

Source: Mission Possible Partnership Power Prices model; Climate Change Committee - Deep-Decarbonization Pathways for UK Industry; NREL ATB Commercial Storage Data

AFFORDABILITY INPUTS | SPAIN 6+6 HOURS SCENARIO

PROJECTED POWER PRICE

EUR/MWh



ES: 6+6 hours scenario charges for:

- 6h during the night, at baseload prices *modelled using EEX Spanish Power futures*
- 6h during Solar PPA window (10.00-16.00) *modelled using Standalone Solar prices for Spain*

Source: Mission Possible Partnership Power Prices model; EEX Spanish Power Futures

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AFFORDABILITY INPUTS | GAS AND CARBON TAX

Gas Tax

COUNTRY	SCENARIO	UNIT	2023	2030
NL	BAU	EUR/MWh	4.46	6.60
FR	BAU	EUR/MWh	7.20	7.20
DE	BAU	EUR/MWh	5.10	5.10
UK	BAU	EUR/MWh	9.00	9.00
DK	BAU	EUR/MWh	6.00	6.00
ES	BAU	EUR/MWh	3.70	3.70
US	BAU	EUR/MWh	0.00	0.00

Carbon Tax

COUNTRY	SCENARIO	UNIT	2023	2030
EU + UK	BAU	EUR /tCO2	80.00	125.00
DK	BAU	EUR /tCO2	80.00	150.00
US	BAU	EUR /tCO2	0.00	0.00

Source: Eurostat - Gas prices components for non-household consumers - annual data (2022); Belastingdienst, CPI Indexed; Climate Change Levy rates - UK Government (2023); Taxes – Manufacturing Exemptions - Texas Tax Authority; Denmark Will Introduce Corporate Carbon Tax 2025 – Enerdata (2023); Systemiq analysis

CONTENTS

LEVERS TO REACH AFFORDABILITY TIPPING POINTS – NON-GOVERNMENT INTERVENTION

1. POWER MARKET MOVES

Potential LCOH change based on day-ahead price volatility in the power market, derived from taking the average percentage price movements historically, from 2015 to 2023, excluding the extraordinary moves caused by the Ukraine war. This price movements range from15% to 50%, which 30% was taken as the assumption used and applied to the 2030 projected wholesale market price, and increasing the B6 discount by 50%. Gas price fluctuations ranges from 35% to 45% based on futures.

2. SITE OPTIMISATION

The lower end of this range is based on a 10% improvement on general LCOH. The upper end of this range is based on difference in LCOH between grid connected and onsite renewables, or the difference between the general and lowest real use case LCOH.

3. TECHNOLOGY PROGRESSION

Reduction in LCOH based on further capital expenditure (CapEx) changes due to ETES technology improvement in 2030. The additional CapEx reduction is from Renewable Thermal Collective report.

4. VALUING DECARBONISATION

Net reduction in LCOH from willingness to pay additional "green premiums" on low-carbon products. The assumed percentage reduction is average of "Green" premium from 4 different sectors (with respective range of price premiums): Textile (15%-25%), Steel (40%), Textiles (15%), and Chemicals (10%-60%). The average of these 4 sectors are 25-30%, and then adjusted to LCOH contribution by assuming energy is 20% of Cost of Goods Sold. This calculation (20% of 25-30%) results in a net reduction on LCOH of 5 to 6%.

LEVERS TO REACH AFFORDABILITY TIPPING POINTS – GOVERNMENT INTERVENTION

5. GRID SERVICES

Additional LCOH reduction from participation of ETES in balancing and ancillary services. This is derived from an estimated 20,000 to 40,000 EUR/MWh/year revenue from flex services today (from technology providers) with a 50% discount for market uncertainty. This revenue is pro-rated with EU and US wholesale baseload power prices to obtain a US estimate.

6. GRID COST REFORM

Two potential levers depending on what has already been actioned: 1) reduction of grid fees to lowest price level or 2) 30-50% reduction in grid fees for interruptible connections

7. SUBSIDIES

Size of subsidy is equivalent to the gap between general 2030 ETES LCOH and 2030 gas boilers, i.e. the subsidy required if no other levers were applied.

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